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Possible signature of hypernova nucleosynthesis in a beryllium rich halo dwarf*

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ABSTRACT
As part of a large survey of halo and thick disc stars, we found one halo star, HD 106038, exceptionally overabundant in beryllium. In spite of its low metallicity, [Fe/H] = -1.26, the star has log(Be/H) = -10.60, which is similar to the solar meteoritic abundance, log(Be/H) = -10.58. This abundance is more than ten times higher the abundance of stars with similar metallicity and cannot be explained by models of chemical evolution of the Galaxy that include the standard theory of cosmic-ray spallation. No other halo star exhibiting such a beryllium overabundance is known. In addition, overabundances of Li, Si, Ni, Y, and Ba are also observed. We suggest that all these chemical peculiarities, but the Ba abundance, can be simultaneously explained if the star was formed in the vicinity of a hypernova.

Key words: stars: abundances – stars: chemically peculiar – stars: individual: HD 106038

1 INTRODUCTION

The single stable isotope of beryllium, ^{9}Be, is a pure product of cosmic-ray spallation of heavy (mostly CNO) nuclei (Reeves, Fowler & Hoyle 1970). Analyses of Be abundances in metal poor stars (Molaro et al. 1997; Boesgaard et al. 1999) have found a relationship between [Fe/H][1] and log(Be/H) with slope close to one, and between [O/H] and log(Be/H) with slope between 1 and 1.5, depending on the oxygen indicator used. Independently of the behaviour of the [O/Fe] ratio at lower metallicities, these results suggest a primary production of Be in the early Galaxy (King 2001).

As a primary element, and assuming cosmic-rays to be globally transported across the early Galaxy, Be may show a smaller scatter than the products of stellar nucleosynthesis (Suzuki & Yoshii 2001) at a given time, suggesting its potential use as a cosmochronometer.

So far, the linear relations appear to be very tight, showing a surprisingly low scatter comparable to the measurement errors. This picture, however, might change with the increase of the samples analysed, as hinted by the results of Boesgaard & Novicki (2006). Nevertheless, turn-off stars of the globular clusters NGC 6397 and NGC 6752 were found (Pasquini et al. 2004, 2007) to have the same Be abundance of field stars of the same metallicity. This strongly support the production of Be to be a global process. Ages derived from these abundances, in a comparison with a model of the evolution of Be with time (Valle et al. 2002), show an excellent agreement with ages derived from theoretical isochrones, supporting the use of Be as a cosmochronometer. Moreover, Pasquini et al. (2005) showed that Be abundances could be used to study the differences in the time scales of star formation in the halo and the thick disc of the Galaxy.

In this letter, we report the discovery of an extremely Be enriched halo star, HD 106038, with an abundance 1.2 dex higher than stars of similar metallicity. This unique star deviates considerably from the observed relations of Be with Fe and O. It was identified during the analysis of a large

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[1] [A/B] = log [N(A)/N(B)]$_\star$ - log [N(A)/N(B)]$_\odot$

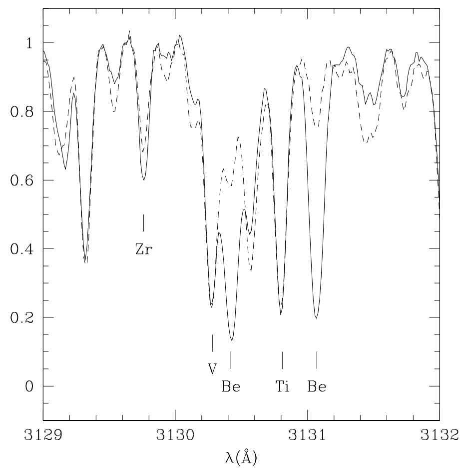

Figure 1. Comparison between the spectra of HD 106038 (solid line) and of HIP 7459 (dashed line), a star with close atmospheric parameters and similar metallicity, in the Be region. The dominating element of the nearby blended features are also indicated. The V and Ti features have the same strength in the two stars while some difference in the Zr line is noted.

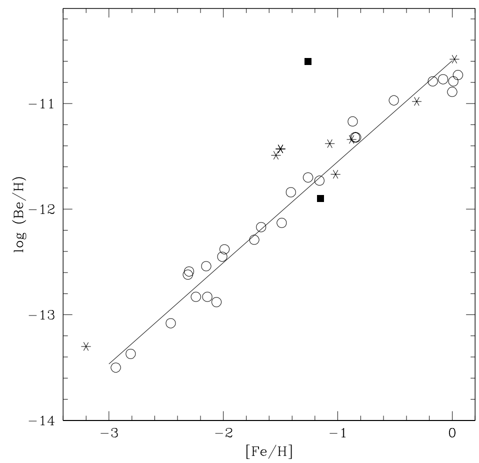

Figure 2. The abundance of Be as a function of [Fe/H]. The stars HD 106038 and HIP 7459 (filled squares) are compared to the linear relation defined by the stars from Boesgaard et al. (1999) (open circles). The starred symbols are the stars from Boesgaard et al. (1999) and Boesgaard & Novicki (2006). Two of them deviate from the linear relation by $\sim$ 0.50 dex.

sample containing near to one hundred halo and thick disc stars (Smiljanic et al. 2008, in preparation).

Neither the standard scenario for Be production, involving spallation of cosmic-rays on nuclei of the interstellar medium (Valle et al. 2002), nor the superbubbles (SBs) scenario (Parizot 2000) seem to be able to produce such Be enriched objects. The SBs model predict a scatter in the Be abundance (Parizot & Drury 2000) that may explain the stars found by Boesgaard et al. (1999) and Boesgaard & Novicki (2006) which have similar atmospheric parameters but Be abundances differing by $\sim$ 0.5 dex. The very high Be abundance in HD 106038, however, would require an extremely poor mixing of the SNe ejecta with the ISM which seems to be difficult to justify (Parizot 2000).

To the best of our knowledge, there is only one other case of extremely Be enhanced star in the literature.[2] The star J37 of the open cluster NGC 6633 was found by Ashwell et al. (2005) to have log (Be/H) = -9.0 ± 0.5. The chemical peculiarities of star J37 might be best explained by the accretion of rocky material similar to chondritic meteorites (Ashwell et al. 2005). As we shall see below, the accretion of such a material is unlikely for our population II star.

2 DATA AND ANALYSIS

The science raw data and calibration files of HD 106038 were retrieved from the ESO science archive facility. The spectra were originally obtained in 2000 April 12 with the UVES spectrograph (Dekker et al. 2000) of the ESO VLT at Cerro Paranal, Chile. The data of HIP 7459 (CD−61 282), a halo star used as comparison in this work, were obtained in 2005 September 22 with the same instrument. The spectra have R $\sim$ 45000 and a final S/N $\sim$ 70 in the Be region.

For both stars, we adopt the atmospheric parameters derived by Nissen & Schuster (1997). The parameters were calculated with the standard spectroscopic approach using Fe I and Fe II lines (Table 1). We refer the reader to the original work for more details.

Abundances (Table 1) were derived through the synthesis of the spectrum around the Be II resonance lines at 3131.065 Å and 3130.420 Å. The codes for calculating synthetic spectra are described in Coelho et al. (2005). Grids of model atmospheres without overshooting calculated by the ATLAS9 program (Castelli & Kurucz 2003) were adopted. The list of atomic lines is that compiled by Primas et al. (1997) and the molecular line list is described in Coelho et al. (2005). A solar Be abundance was derived using the UVES solar spectrum. We estimate the total uncertainty from atmospheric parameters, continuum placement, and synthetic fit affecting the Be abundance to be $\sigma = \pm 0.13$ dex. Zero point errors might also be present due, for example, to the adopted model atmosphere. However, we are conducting a differential analysis and these should cancel out in a comparison between similar stars.

A comparison between the spectra of the two stars is shown in Figure 1, in which the extreme enhancement of the Be lines of HD 106038 when compared to the normal HIP 7459 is clear, confirming its very high Be overabundance.

We show in Figures 2 and 3 these two stars in the [Fe/H] vs. log (Be/H) and [O/H] vs. log (Be/H) diagrams, respectivelly, together with the stars from Boesgaard et al. (1999) and Boesgaard & Novicki (2006). Of particular interest are the two stars from Boesgaard & Novicki (2006) that deviate from the linear trend. The anomalous position of HD 106038 clearly stands out.

[2] We exclude from the discussion the chemically peculiar A or F stars with enhanced Be lines. The peculiar abundances of these stars are thought to be caused by effects of diffusion. As shown by Richard, Michaud & Richer (2002), these effects do not result in overabundances in stars with similar temperature and metallicity as HD 106038.

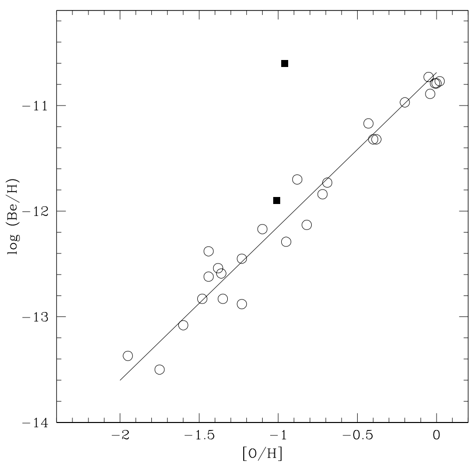

Figure 3. The abundance of Be as a function of [O/H]. Symbols are as in Fig. 2. The stars of Boesgaard & Novicki (2006) are not shown since O abundances were not derived by these authors.

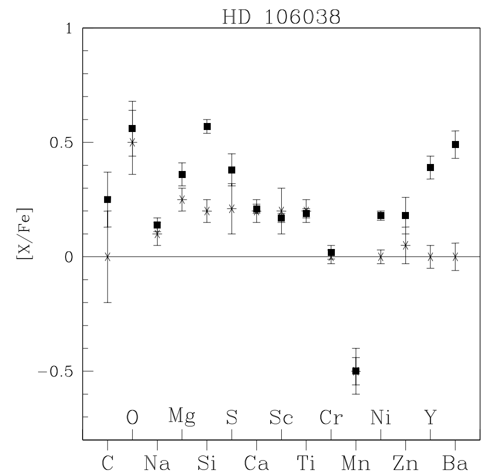

Figure 4. Elemental abundances, [X/Fe], of HD 106038 determined in the literature. The abundances are represented by the full squares. In this case the error bar denotes the actual uncertainty quoted by the original work. The starred symbols indicate the mean abundance of that element for the remaining sample as found in the same work. In this case the error bar indicates the range of abundances for that given element in the original work. HD 106038 is clearly overabundant in Si, Ni, Y, and Ba, and show slightly larger abundances of C, S, Mg, and Zn when compared to the mean of the original samples.

Table 1. The adopted atmospheric parameters and beryllium abundances derived using synthetic spectra for HD 106038, HIP 7459, a comparison star, and for the Sun.

star	$T_{\rm eff}$ K	log g	ξ km s^{-1}	[Fe/H]	log(Be/H)
Sun	5777	4.44	1.00	0.00	−10.9
HD 106038	6046	4.46	1.34	−1.26	−10.6
HIP 7459	5909	4.46	1.23	−1.15	−11.9

2.1 Chemical abundances in the literature

Information on other chemical abundances might help understanding the origin of the Be overabundance. An overabundance of CNO elements, for example, would offer a good explanation for the enhancement, since these elements are dominant in the production of Be by spallation processes.

Asplund et al. (2006) determined a lithium abundance of A(^{7}Li) = 2.48 and claimed a detection of ^{6}Li, ^{6}Li/^{7}Li = 0.031, compatible with the other 8 detections out of a sample of 26 stars. The high ^{7}Li abundance, however, results in a high ^{6}Li abundance, A(^{6}Li) = 0.97, while the mean for the other detections is 0.80.

Its ^{7}Li is particularly remarkable since it is larger than the Spite plateau (Spite & Spite 1982). The plateau as found by Asplund et al. (2006) is at 2.22, which means HD 106038 has an abundance excess of $\Delta A(^7{\rm Li}) = 2.13$. Given that lithium is also expected to be produced by cosmic-ray spallation it seems safe to conclude that both ^{7}Li and Be overabundances have the same origin.

Abundances of other elements available in the literature are shown in Figure 4. Abundances of Na, Ca, Mg, Si, Ti, Cr, Ni, Y, and Ba are from Nissen & Schuster (1997). The carbon abundance is taken from Fabbian et al. (2006) and oxygen from Meléndez et al (2006). Abundances of Mn and Sc are from Nissen et al. (2000) and of S and Zn from Nissen et al. (2007). In the same figure we also show the mean abundances of the samples analysed in these same works for comparison.

In addition to Be and Li, the star also shows clear enhanced abundances of Si, Ni, and of the neutron capture elements Y and Ba. An enrichment in s-process elements may explain the enhanced Zr line in Figure 1. We also note the possibly larger amounts of C, S, Mg, and Zn, though these remain marginally compatible with the mean abundances of the samples.

3 DISCUSSION

Since the standard scenario for cosmic-ray spallation does not explain the enhancement of Be in HD 106038, a peculiar and/or rare event may be related to its formation. A combination of two or more rare events to produce the observed features is unlikely, we therefore concentrate on single events.

To reproduce the very particular chemical pattern of HD 106038, a nucleosynthetic site must be able to overproduce Si and Ni without overproducing other α and iron group elements. Elements in normal halo stars with the same metallicity as HD106038 come mostly from SNe II. It is therefore unlikely that the same SNe II may produce the observed enhanced [Si/Fe] and [Ni/Fe] ratios. Moreover, it has about 16 times more Be than what models involving SN II predict for its metallicity (Valle et al. 2002). SNe Ia produce large amounts of Fe, Ni, and other iron group elements but are not expected to produce large amounts of O and Si (Iwamoto et al. 1999). Therefore, in case of a contribution from SNe Ia, ratios such as [O/Fe] and [Si/Fe] would fall below normal halo stars, contrary to what is observed. Moreover, SNe Ia are expected to produce about one order of magnitude less spallation products than SN II (Fields et al. 2002).

All these features, however, may possibly be found in the ejecta of a hypernova (HNe), which can be enriched in both intermediate mass elements (as S and Si) as in iron group elements (Nakamura et al. 2001; Podsiadlowski et al. 2002). Moreover, HNe can produce large amounts of Be and Li by spallation (Fields et al. 2002; Nakamura & Shigeyama 2004). Therefore, we suggest that the material which formed this star was probably contaminated by the nucleosynthetic products of a HNe.

3.1 Hypernova

Hypernovae are core-collapse SNe (usually of type Ic) with exceptionally large kinetic energy production, resulting in spectra dominated by very broad absorption line blends (Mazzali et al. 2000). The energy released in the explosion can be one order of magnitude larger than that of normal core-collapse SNe (Iwamoto et al. 2003). Some hypernovae, typically the most massive and energetic events, are linked to Gamma-Ray bursts (Iwamoto et al. 1998).

Fields et al. (2002) and Nakamura & Shigeyama (2004) calculated the yields of spallation products resulting from HNe explosions. While Nakamura & Shigeyama (2004) calculate the energy distribution of the ejecta with a hydrodynamic code and solve the cosmic-ray transfer equation, Fields et al. (2002) use an empirical formula for the energy distribution and do not solve the transfer equation but adopt an approximation to have the mass fraction of the ejecta that produces the spallation products. Nakamura & Shigeyama (2004) claim the simplifications adopted by Fields et al. (2002) to overestimate the yields by a factor ~ 3.

The yield of Be per HNe can be one or two orders of magnitude larger than the one per SNe II (Fields et al. 2002; Nakamura & Shigeyama 2004). However, as a rare event, they are not major contributors of Be in the Galaxy. Fields et al. (2002) predict ^{7}Li/^{9}Be ~ 8.6 and Be/O $\sim 5.6 \times 10^{-7}$ (both ratios by number). The calculations by Nakamura & Shigeyama (2004) predict ^{7}Li/^{9}Be ~ 4.2, also by number. Both predictions are close to what is observed in HD 106038; the ratio between the observed excess of ^{7}Li and ^{9}Be is ^{7}Li/^{9}Be $= 5.6$ (while the HNe is expected to have produced all the observed Be abundance, it is responsible only for the excess of Li with respect to the primordial plateau). We cannot estimate the contribution of the possible HNe on the observed oxygen abundance, thus only a lower limit can be placed, Be/O $>1.9 \times 10^{-7}$, given by the assumption that all the observed oxygen has been produced by the HNe.

Both models, however, predict much more ^{6}Li than observed, ^{7}Li/^{6}Li ~ 1.9 by Fields et al. (2002) and ^{7}Li/^{6}Li ~ 1.2 by Nakamura & Shigeyama (2004), by number. The observed ratio between the excess of ^{7}Li and the ^{6}Li abundance is ^{7}Li/^{6}Li $\leqslant 15$. We consider this ratio an upper limit since, given its fragility, some ^{6}Li has probably been destroyed in previous evolutionary phases. The production of Be without a corresponding production of ^{6}Li would be extremely difficult to understand.

Nucleosynthetic calculations by Nakamura et al. (2001) find the ejecta of HNe to have smaller amounts of C and O and larger amounts of Si, S, and Ar, when compared to normal SNe. Nakamura et al. (2001) and Nomoto et al. (2006) also note larger [(Zn,Co)/Fe] and smaller [(Mn,Cr)/Fe] ratios. An overabundance of Zn, which is not observed, can be avoided with a deeper mas cut[3], which would also result in a larger [Ni/Fe] (Nomoto et al. 2006). These are in qualitatively agreement with the observations, supporting the HNe hypothesis.

The weak s-process in massive stars seems to efficiently produce only elements with a mass number[4] up to 90 (Rayet & Hashimoto 2000). The Y overabundance may require an enhanced flux of neutrons, which would also contribute to the production of Ni. The Ba overabundance, however, is more difficult to understand. It is not clear whether this same mechanism would result in the overproduction of Ba. Moreover, a significant amount of Ba is expected to be produced only by the main s-process in AGBs or by the r-process, usually associated to massive stars. Since pollution by AGBs is not possible (see below), the Ba overabundance is likely a product of a massive star. For example, although not expected, Mazzali, Lucy & Butler (1992) found Ba to be overabundant by a factor of 5 in the spectrum of SN 1987A. Although Ba might pose a problem for our scenario, we recall that theoretical predictions for the r-process elements in HNe are not available. Therefore, whether this scenario is able to explain the Ba abundance is still an open question.

The HNe scenario, at least qualitatively, is able to explain most features observed in HD 106038 within a single peculiar event. More work, however, is still needed to show whether the scenario still holds quantitatively. A detailed comparison with nucleosynthetic predictions of theoretical models is necessary to validate or not the HNe hypothesis.

3.2 Other scenarios

In this subsection we present some alternative scenarios for the origin of the Be enhancement in HD 106038, which were discarded for the reasons presented below.

A pollution by AGB stars, or any kind of evolved star, can at once be discarded. Although these may explain the s-process elements, and maybe Li, they do not explain the Be overabundance. On the contrary, the material ejected by an AGB or by a massive star, after successive mixing events, would be depleted in Be.

The SBs scenario (Parizot 2000) would be able to reproduce the observed Li/Be and Be/O ratios only with an extreme model where particles are accelerated from pure SNe ejecta. The SBs evolution models, however, predict that most material inside of a SB comes from the ISM. Moreover, the remaining chemical peculiarities are not typical of SNe II ejecta and thus can not be explained within the same scenario.

Another possibility is the engulfing of a sub-stellar object, a planet or planetesimals debris as in star J37 of the open cluster NGC 6633 (Ashwell et al. 2005). This, however, can be excluded with a robust quantitative argument. The accreted material would be confined to the surface convective layer of the star. In a metal poor star this layer is much shallower than in a solar metallicity star. With the equation given by Murray et al. (2001) we estimate the surface convective layer of HD 106038 to have $\sim 4.5 \times 10^{-3}$ M$_\odot$. The

[3] The coordinate, in mass, separating the part of the star that is ejected and the one that forms the remnant.

[4] The mass number of Y is A = 89 and of Ba is A $\sim$ 136.

mass of Be in this layer is $\sim 7.7\times10^{-13}$ $M_\odot$ while in a star with normal abundance of Be it would be $\sim 4.8\times10^{-14}$ $M_\odot$. Assuming the accreted material to have a composition similar to chondrites meteorites (Lodders 2003) a mass of Fe of 5.3×10^{-6} $M_\odot$ would also be accreted with the required mass of Be. However, the total mass of Fe in the convective layer of the star is $\sim 3.3\times10^{-7}$ $M_\odot$. In this scenario all, or almost all, Fe in the convective layer of the star would come from the accreted material. HD 106038 would then originally be a population III metal free star; an extremely unlikely possibility. In addition, we note that the most metal poor star found to host planets has [Fe/H] = -0.68 (Cochran et al. 2007).

A longer exposure to EPs would be the natural explanation if HD 106038, for some reason, was younger than halo stars of the same metallicity. Its Be abundance would be a result of the accumulated action of EPs in a cloud where star formation was, somehow, delayed. Its Be abundance higher than the solar photospheric one could be a sign of a solar or younger age, in agreement with the suggestion of Pasquini et al. (2004) that Be abundances could be used as a cosmic clock. The position of the star in the HR diagram, although not favourable for a good age determination, favours an older age and argues against this hypothesis.

If the star originated in or near the Galactic centre, the enhanced star formation and supernovae events could provide an enhanced EPs flux. This flux might also originate from a non-stellar source such as the central black hole. A bulge origin for the star, however, seems unlikely. In particular the abundances of Ni, Y, and Ba are not compatible with the ones of bulge stars (McWilliam & Rich 1994). Since it requires another source for the Ni and s-process overabundances, we also discard this hypothesis.

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REFERENCES

Ashwell, J. F., Jeffries, R. D., Smalley, B., Deliyannis, C. P., Steinhauer, A., King, J. R., 2005, MNRAS, 363, L81
Asplund, M., Lambert, D. L., Nissen, P. E., Primas, F., Smith, V. V., 2006, ApJ, 644, 229
Boesgaard, A. M., Deliyannis, C. P., King, J. R., Ryan, S. G., Vogt, S. S., Beers, T. C., 1999, AJ, 117, 1549
Boesgaard, A. M., Novicki, M. C., 2006, ApJ, 641, 1122
Castelli, F., Kurucz, R. L., 2003, in Proceedings of the IAU Symp. 210, A20
Cochran, W. D., Endl, M., Wittenmyer, R. A., Bean, J. L., 2007, ApJ, 665, 1407
Coelho, P., Barbuy, B., Meléndez, J., Schiavon, R. P., Castilho, B. V., 2005, A&A, 443, 735
Dekker, H., D'Odorico, S., Kaufer, A., Delabre, B., Kotzlowski, H., 2000, SPIE, 4008, 534
Fabbian, D., Asplund, M., Carlsson, M., Kiselman, D., 2006, A&A, 458, 899.
Fields, B. D., Daigne, F., Cassé, M., Vangioni-Flam, E., 2002, ApJ, 581, 389
Iwamoto, K., Brachwitz, F., Nomoto, K., Kishimoto, N., Umeda, H., Hix, W. R., Thielemann, F. K., 1999, ApJS, 125, 439
Iwamoto, K., Mazzali, P. A., Nomoto, K., Umeda, H., et al., 1998, Nature, 395, 672
Iwamoto, K., Nomoto, K., Mazzali, P. A., et al., 2003, Lecture Notes in Physics, 598, 243
King, J. R., 2001, AJ, 122, 3115
Lodders, K., 2003, ApJ, 591, 1220
Mazzali, P. A., Iwamoto, K., Nomoto, K., 2000, ApJ, 545, 407
Mazzali, P. A., Lucy, L. B., Butler, K., 1992, A&A, 258, 399
McWilliam, A., Rich, R. M., 1994, ApJS, 91, 748
Meléndez, J., Shchukina, N. G., Vasiljeva, I. E., Ramírez, I, 2006, ApJ, 642, 1082
Molaro, P., Bonifacio, P., Castelli, F., Pasquini, L., 1997, A&A, 319, 593
Murray, N., Chaboyer, B., Arras, P., Hansen, B., Noyes, R. W., 2001, ApJ, 555, 801
Nakamura, K., Shigeyama, T., 2004, ApJ, 610, 888
Nakamura, T., Umeda, H., Iwamoto, K., Nomoto, K., Hashimoto, M., Hix, W. R., Thielemann, F. K., 2001, ApJ, 555, 880
Nissen, P. E., Akerman, C., Asplund, M., Fabbian, D., Kerber, F., 2007, A&A, 469, 31
Nissen, P. E., Chen, Y. Q., Schuster, W. J., Zhao, G., 2000, A&A, 353, 722
Nissen, P. E. & Schuster, W. J., 1997, A&A, 326, 751
Nomoto, K., Tominaga, N., Umeda, H., Kobayashi, C., Maeda, K., 2006, Nuclear Physics A, 777, 424
Parizot, E., 2000, A&A, 362, 786
Parizot, E., Drury, L., 2000, A&A, 356, L66
Pasquini, L., Bonifacio, P., Randich, S., Galli, D., Gratton, R. G., 2004, A&A, 426, 651
Pasquini, L., Bonifacio, P., Randich, S., Galli, D., Gratton, R. G., Wolff, B., 2007, A&A, 464, 601
Pasquini, L., Galli, D., Gratton, R. G., Bonifacio, P., Randich, S., Valle, G., 2005, A&A, 436, L57
Podsiadlowski, P., Nomoto, K., Maeda, K., Nakamura, T., Mazzali, P., Schmidt, B., 2002, ApJ, 567, 491
Primas, F., Duncan, D. K., Pinsonneault, M. H., Deliyannis, C. P., Thorburn, J. A., 1997, ApJ, 480, 784
Rayet, M., Hashimoto, M., 2000, A&A, 354, 740
Richard, O., Michaud, G., Richer, J., 2002, ApJ, 580, 1100
Reeves, H., Fowler, W. A., Hoyle, F., 1970, Nature, 226, 727
Spite, F., Spite, M., 1982, A&A, 115, 357
Suzuki, T. K., Yoshii, Y., 2001, ApJ, 549, 303
Valle, G., Ferrini, F., Galli, D., Shore, S. N., 2002, ApJ, 566, 252